# Science with an 8-meter to 16-meter Optical/UV Space Telescope

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## ABSTRACT

A key component of our 2008 NASA Astrophysics Strategic Mission Concept Study entitled "*An Advanced Technology Large-Aperture Space Telescope: A Technology Roadmap for the Next Decade*" is the identification of the astrophysics that can be uniquely accomplished using a filled, large-aperture UV/optical space telescope with an angular resolution 5 – 10 times better than JWST. We summarize here four research areas that are amongst the prime drivers for such an advanced astronomical facility: 1) the detection of habitability and bio-signatures on terrestrial mass exoplanets, 2) the reconstruction of the detailed history of the assembly of stellar mass in the local universe, 3) establishing the mass function and characterizing the accretion environments of supermassive black holes out to redshifts of z ~ 7, and 4) the precise determination of growth of structure in the universe by kinematic mapping of the dark matter halos of galaxies as functions of time and environment.

**Keywords:** Large Space Telescopes, UV/Optical Space Telescopes, Astrophysics, Astrobiology

## 1. INTRODUCTION

The greatest leaps in our understanding of the universe typically follow the introduction of radically new observational capabilities that bring previously unobserved phenomena into view. Some, such as the unambiguous detection of life on an Earth-like planet orbiting another star, will be profound yet conceivable. Others are entirely beyond our imagination. All forever change our view of our place in the universe. But even the great advances of knowledge that would follow finding faint traces of life on extra-solar planets will depend upon discoveries that can only be made by space-based telescopes with apertures of 8 meters or more. The **Advanced Technology Large-Aperture Space Telescope (ATLAST)** is envisioned as a flagship mission of the 2025 – 2035 period, designed to address one of the most compelling questions of our time – *Is there life elsewhere in our Galaxy?* It will have the capabilities required to explore the nearest ~1,000 stars capable of harboring life for Earth-size planets and characterize their spectra. ATLAST will also be a next generation UV/Optical Great Observatory, in the model established by the Hubble Space Telescope, capable of achieving breakthroughs in a broad range of astrophysics and adaptable to addressing scientific investigations yet to be conceived. Indeed, such a telescope would revolutionize the study of galaxy evolution, enabling, for the first time, measurements of the kinematics of both the gaseous and stellar components of the smallest dwarf galaxies. It would yield such precise constraints on hierarchical structure formation models that a new era of "precision galaxy evolution" would ensue.

The combination of high angular resolution and high sensitivity is, increasingly, a science driver in astrophysics. As such, the most compelling astrophysical questions to be addressed in the 2020 era will,

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like those today, be pursued using data obtained from both space-based and ground-based telescopes. Indeed, without this synergy, key elements to our understanding of the cosmos would remain unknown. The impressive capabilities anticipated for ground-based observatories in the upcoming decade (e.g., 20 to 40-meter class optical telescopes, ALMA, and potentially the SKA near the end of the decade) will redefine the existing synergy between ground and space telescopes. Optimistic advances, over the next decade, in Multi-Conjugate Adaptive Optics (MCAO) and Ground-Layer Adaptive Optics (GLAO) for large aperture ground-based telescopes[1],[2],[3],[4] may enable intermediate to high Strehl ratio (~40-80%) performance over fields of view of perhaps up to 2 arcminutes across for wavelengths longwards of ~1 μm. For the foreseeable future, however, space will be the optimal environment for optical observations that require any combination of very high-angular resolution and precise wavefront control over fields of view larger than ~2 arcminutes or at wavelengths shorter than ~1 micron, very high sensitivity, very stable PSF performance across the field of view, high photometric precision and accuracy in crowded fields, and very high stability of all these performance parameters over tens to hundreds of hours of exposure time. And, of course, UV observations are only doable from space.

On the ground, the relatively lower cost (vs. space) of constructing very large (>20-m) aperture telescopes brings the ability to capture a significant number of photons from the very faintest sources enabling spectroscopic observations not achievable from orbit and the upgradeable instrumentation keeps the ground-based telescopes relevant for decades. The very high atmospheric sky-background at 2 μm and longer, however, makes space the preferred location for facilities making leading edge observations in these passbands. At wavelengths shorter than 2 μm, there will be a trade-off between the full spectrum, wide-field, highly stable diffraction-limited capabilities of an optical space telescope and the near-term reality that the largest ground-based apertures will typically have 5 – 20 times the collecting area of the largest space-based apertures.

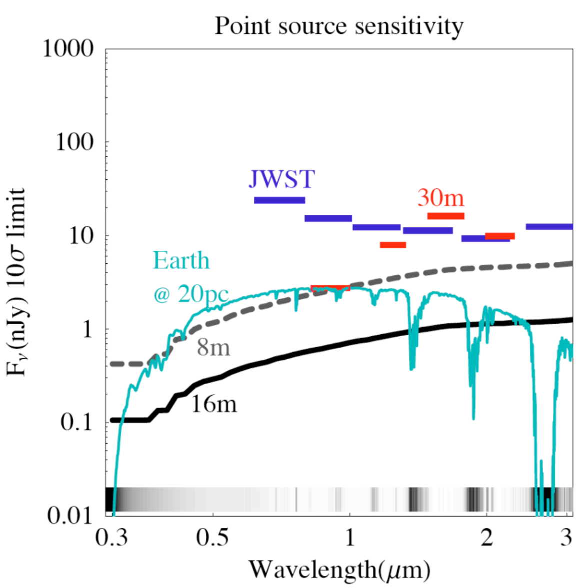


**Figure 0**: 10-σ point source sensitivity (in nanoJy) for broadband (R = 4) imaging in a 1-hour exposure for ATLAST 8-m and 16-m, JWST, and a 30-m ground-based telescope with MCAO. The superposed spectrum is that of a terrestrial exoplanet at a distance of 20 pc.

**Figure 1 s**hows the broadband (R~4) photometric sensitivities for a point source, in a 3600 second integration, for an 8-m and 16-m space telescope, a 30-m ground-based telescope, and the James Webb Space Telescope (JWST is an IR-optimized 6.5-m facility). For the 30-meter ground-based telescope, diffraction-limited performance is assumed down to 1 μm. The spectrum of an Earth-like exoplanet at a distance of 20 pc is shown as a reference. Characterization of such an exoplanet would require a large (aperture of ~10-m or more) space-based telescope. Predicting the point source sensitivity of a 30-m ground-based telescope in the optical band (0.4 – 0.8 μm) depends critically on how the Strehl ratio decays bluewards of the assumed 1 μm "AO limit" and we have not attempted that computation here. Characterization of exoplanets is just one example of an important astrophysical investigation where space has a distinct advantage. We discuss this case and a few others in more detail below. However, for many applications, such as the pursuit of a comprehensive and predictive theory of star formation, data from both space-based and ground-based facilities will be required and complimentary, each filling in key gaps in our present knowledge.

Human ingenuity will continue to drive the pursuit of many astrophysical investigations from whatever the current state-of-the-art facilities are available, regardless of whether they are in space or on the Earth's surface. But the scientific legacy of the Hubble Space Telescope clearly demonstrates that having access to the ~4 octaves of wavelength from 0.1 to 2 μm from a space-borne telescope of large aperture will be an essential part of future astrophysical investigations.

## 2. SCIENCE OBJECTIVES FOR A LARGE UV/OPTICAL SPACE TELESCOPE

### *2.1 The Search for Life on Exoplanets*

With more than 250 known exosolar planets and planetary systems, there is a general belief among astronomers, albeit as yet unverified by data, that many terrestrial-mass planets orbit nearby stars and some should have detectable signatures of life. If life alters the atmospheres of other planets as it has on Earth through the production of oxygen and $CO_2$, for example, we could see these chemical signatures in spectra of the planets[5],[6]. Because the Earth's atmosphere blocks many of the interesting spectral lines and because the required levels of starlight suppression are not possible when looking through the variable atmosphere, only a space telescope will be able to discern biosignatures in the faint spectra of the planet.

**Table 1: Exoplanet Host Star Sample Size vs. Telescope Diameter**

| $D_{TEL}$ (meters) | Expected #Transits | #Coronagraphic All | #Coronagraphic Solar |
|---|---|---|---|
| 2 | 0 | 4 | 0 |
| 4 | 1 | 35 | 13 |
| 8 | 5 | 280 | 101 |
| 16 | 40 | 2240 | 1417 |

**Table 1:** Column 2 gives the number of stars where one could spectroscopically observe a transiting exoplanet over a 5-year interval. Columns 3 and 4 show the number of stars that have their HZ viewable beyond an inner working angle of 3λ/D (~0.077 arcseconds for an 8-m telescope at 1 μm).

Direct detection of biosignatures from terrestrial mass (≤10 $M_{Earth}$) exoplanets within the local solar neighborhood (up to ~100 parsecs) will clearly be a major observational objective of the next 25 years. However, it is a problem that is nearly impossible to attack with space telescopes a few meters in size and completely undoable from the ground even with 30-m class telescopes. The main difficulty is that terrestrial planets at temperatures amenable to life as we know it – roughly between the freezing and boiling points of water (*a.k.a. the habitable zone* or HZ) – are very faint, and it takes an excessively long time to gather spectra suitable for studying life's signatures. As a reference, an Earth twin around a solar-like star at a distance of 20 parsecs (pc) is ~30.5 mag (~0.015 photons/sec per square-meter of aperture integrated over a broad visible light bandpass). The observational difficulties, however, decrease dramatically with increasing telescope diameter. Larger space telescopes can study planets farther from the solar system, and because the accessible volume of space is proportional to the cube of the limiting distance, itself proportional to the telescope diameter, the sample sizes increase rapidly with increasing telescope aperture. Direct observations benefit from a combination of larger collecting area and higher angular resolution, meaning the sample sizes grow even faster than $D_{tel}^3$, increasing by an order of magnitude for each doubling of diameter.

Sample size is a key issue in setting the minimum required telescope aperture needed to ensure a scientific outcome worthy of the investment. Beckwith[7], using the SETI catalog of ~18,000 stars, computed the number of candidate stars that are accessible to a characterization survey of exoplanets in the habitable zone[8] as a function of the aperture size of the telescope conducting the survey. The results

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[8] Beckwith assumed a HZ defined by the region where pure water can be in its liquid phase as determined by radiative equilibrium with a star's luminosity. The HZ for any given star can be altered in size by more realistic

are shown in Table 1 and are based on optimistic but not unrealistic performance (e.g., $10^{-10}$ starlight suppression out to an inner working angle of $3\lambda/D$). To compute the expected number of potentially habitable exoplanets one needs to multiply the sample sizes by the fraction of stars that have planets in their habitable zones (a parameter called eta_earth, $\eta_\oplus$). Ultimately, one would further multiply by the fraction of those HZ planets that exhibit detectable biosignatures ($\eta_{LIFE}$) to get an estimate of the number of detectable life-bearing planets. Only 15% of nearby stars have planets that we can detect with current techniques – planets similar to Jupiter and Saturn – and only about 10% of those lie in the HZ. Better constraints on $\eta_\oplus$ are expected from the COROT and Kepler missions. There are no constraints on $\eta_{LIFE}$ as yet. It will therefore be an enormous advantage to have hundreds of systems available for study to increase the likelihood of discovering a planet with the right properties for life, at least as we know it on Earth. From a sample size consideration alone, a telescope with an aperture of at least 8 meters and more likely closer to 16 meters is, thus, needed for the task. *Operational considerations suggest that smaller precursor missions designed to find the systems with candidate terrestrial planets will make the exoplanet characterizations with ATLAST proceed in a highly efficient manner*. The exposure times required to obtain an R=1000 spectra of an Earth-like planet at 20 pc with S/N = 10 are ~160 hours and ~10 hours for an 8-m and 16-m telescope, respectively. The relatively short exposure time for the 16-m suggests that if it were instrumented with an integral field spectrometer it could efficiently and simultaneously obtain the spectra of all sources detected within the habitable zone *during the initial visit* to each targeted star system. While this does not guarantee a complete census (some planets may be inside the inner working angle at the time of observation), it does greatly speed up the assessment of the exoplanet status of any visible sources as a planetary spectrum will differ dramatically from most background sources that are of similar apparent luminosity (e.g., background sources fainter than ~25th magnitude are nearly all galaxies).

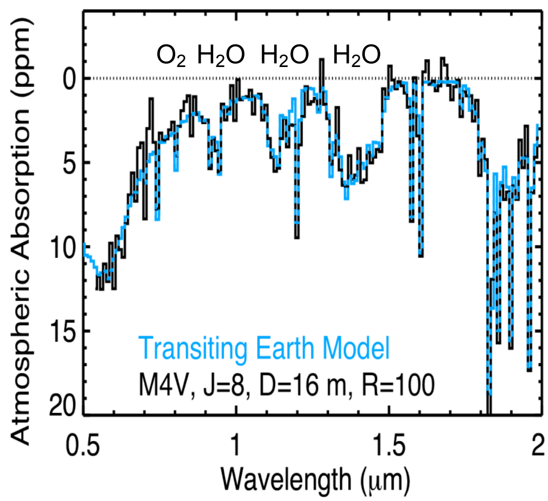


**Figure 2:** ATLAST enables the detection of signs of habitability in tens of Earth-like planets transiting their stars. Blue: model exoplanet spectrum. Black: simulated R=100 spectra of planet with a 16-m space telescope over a 5-year mission. The star here has a spectral type M4V.

A large optical/NIR space telescope could take spectra of terrestrial exoplanet atmospheres by observing transits (**Figure 2**) but the number of such fortuitous alignments over a 5-year period is not large (Table 1). If, however, additional wavefront corrections can eliminate the light from the star either through coronagraphy or alignment of an external occulter (or a combination of the two) then direct images will bring into view hundreds to thousands of additional candidate star/planet systems as illustrated in Table 1. The methodologies and technologies for achieving the required level of suppression (~$10^{-10}$ for an Earth-mass planet at 1 AU in the visible wavelength range) is an area of very active investigation.

### *2.2 Star Formation Histories in the Local Universe: a Key to Cosmic Evolution*

To truly understand how galaxies assemble their stellar mass, we must reconstruct the detailed star formation histories for a large number of galaxies from all morphological types. This can be done if one

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planetary conditions such as oceans with high salinity (which will broaden the HZ), greenhouse effect heating, heating from internal energy sources (e.g., radioactive decay), and atmospheric circulation.

is able to measure accurate colors and luminosities for individual stars in these galaxies. Such "Galactic Archeology" can, at present, only be done for 2 large spiral galaxies (the Milky Way and Andromeda; Brown et al. [8]) and a dozen or so nearby dwarf galaxies (e.g., M32, the Magellanic Clouds). The ability to detect individual solar-luminosity stars in galaxies out to 8 – 15 Megaparsecs (Mpc) will revolutionize the study of stellar populations and galaxy formation because it will increase the number of galaxies we can analyze by more than an order of magnitude. Most importantly, the leap to galaxies well beyond the local group opens up the entire Hubble sequence of elliptical and spiral galaxies for study.

The key to a successful galactic archeological "dig" is the ability to break the age-metallicity degeneracy. Fortunately, one can break this degeneracy with simultaneous photometry of stars on the red giant branch, sub-giant branch and main sequence because age and [Fe/H] behave differently in these three regions of the HR-diagram. The observational requirement to do this is achieving stellar photometry with S/N=5 at a luminosity 0.5 magnitudes fainter than the main sequence turn-off (MSTO)[9] for a color-magnitude diagram consisting of at least 10,000 stars. This allows the stellar age and metallicity distributions to be characterized on a grid with [Fe/H] bins of ~0.5 dex on the metal-poor end and ~0.2 dex on the metal-rich end, and age bins of ~3-4 Gyr on the old end and ~1-2 Gyr on the young end, with sensitivity to sub-populations on the order of ~10% or larger. We can translate these requirements to telescope aperture using the known spatial distribution of galaxies in the Local Supercluster to plot the cumulative number of spiral and elliptical galaxies that would be accessible to such detailed stellar age reconstruction. This is shown in **Figure 3**. To reach the first large elliptical galaxy requires a telescope aperture of 7 meters. To survey a volume with at least 6 massive ellipticals (~11.3 Mpc in distance) requires a 16-meter telescope. The sudden jump in ellipticals seen at a telescope aperture of ~24 meters corresponds to reaching to the Virgo Cluster, ~15 Mpc away. The exposure time to achieve our observational requirement on a galaxy at 11.3 Mpc is ~100 hours with a 16-meter telescope (MSTO + 0.5 mag ~ 35 AB mag at this distance).

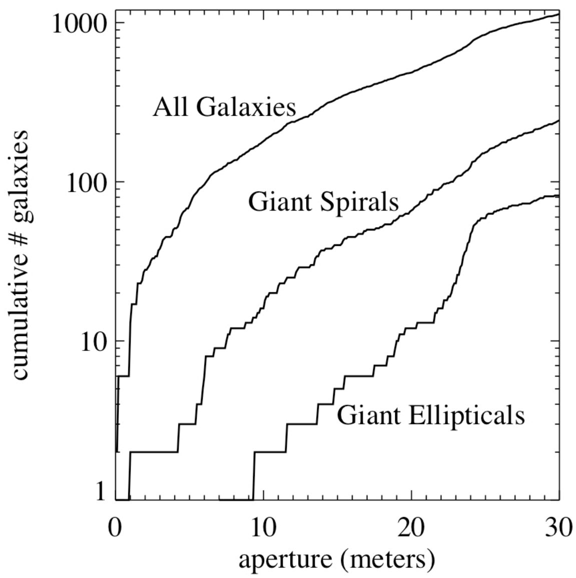


**Figure 3**: Cumulative number of galaxies in which stars 0.5 mag below the MSTO could be measured, as a function of telescope aperture. Assumes two bands at S/N=5.

In the era of JWST, where integrated populations of stars will be observed at very high redshift, we will need to understand the evolutionary history of these nearby galaxies in detail to make sense of the more distant samples. While future (30-m) ground-based telescopes will provide high-resolution imaging, they will not do so with the contrast and stability over the wide fields that are genuinely required for this work. A significant sample of galaxies would yield the star formation history per unit volume in the local universe; the history in the oldest age bins of that local measurement would provide an essential independent check of the measurements by JWST, which will characterize the star formation in the early universe as part of its primary mission.

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9 The Sun is ~0.5 mag fainter than the MSTO in a 12 Gyr population with an intermediate metallicity (20% the solar value). This is the minimum luminosity required to reconstruct the star formation history in a population over the entire age of the universe.

## *2.3 Probing the Environments Near Super-Massive Black Holes*

Galaxy formation is a complex process that we can currently only crudely model. An extremely important but poorly understood part of this process is the role of feedback from the energetic jets and winds powered by the central supermassive black holes (SMBH) that appear to be present in nearly all galaxies. The SMBH in galactic nuclei are indeed large – with masses that are typically ~ $10^7$ - $10^9$ $M_{SUN}$ and which scale approximately with the mass of the host galaxy[9],[10]. Fundamental questions remain about the origin of the relation between the SMBH and their host galaxies, about the precise relation between the energy output from the SMBH and the star formation efficiency and rate within the galaxy, and the nature of the fueling mechanisms and growth of the central SMBH over time. ATLAST should provide unique and new constraints on all of these questions.

The key to unlocking the answers is the ability to obtain spatially resolved images and spectra of the disks of accreting gas in the central regions around SMBHs. These are currently among the least understood of all the phenomena associated with SMBHs in active galactic nuclei (AGN). With physical dimensions of only a few hundred parsecs (corresponding to several thousand Schwarzschild radii), these disks are barely resolved for just a handful of nearby AGN in the local universe, and remain completely unresolved for all other AGN up to cosmological distances. Yet this is one of the most crucial regions to understand in AGN, since it represents the closest gas to the central black hole, thus directly tracing the energetics of the central engine.

**Table 2: SMBH Candidates as a Function of Telescope Aperture**

| $D_{TEL}$ (meters) | Best resolution in arc-seconds (Diff. limited at 0.6 μm) | Highest redshift[10] at which 100 pc can be resolved with UV/opt | Number of potential SMBH Targets |
|---|---|---|---|
| 2 | 0.08” | 0.06 | 10 |
| 4 | 0.04” | 0.10 | 50 |
| 8 | 0.02” | 0.36 | 1,740 |
| 16 | 0.01” | 7.00 | 43,500 |

Resolving the morphology and dynamics of these disks not only in local galaxies but also in sources at cosmological distances, up to at least the epoch of reionization of the universe, will provide an unprecedented breakthrough in our understanding of the physics of the central AGN. Based on the typical size scales of gas disks around nearby SMBHs in the local universe, a spatial resolution of at least 100 pc is required to be able to resolve the disk sufficiently well to obtain a measurement of the mass (see **Figure 4**): for a disk of radius 200 pc, at least two resolution elements (100 pc) are required[11]. Table 2 gives the limits obtained for telescopes of different apertures, assuming they are diffraction-limited above 0.6 μm. The approximate number of potential targets is calculated using current models of black hole growth for each redshift volume. There are significant jumps (factors of >25) in sample size at 8-m and at 16-m. The redshift limit of 7 for the 16-m telescope reflects the fact that it can resolve 100 pc at all lower redshifts as well; beyond z~7 all the emission would shift into the near IR but can potentially still be resolved by a 16-m with sensitivity out to ~2 μm.

In addition to resolving the outer accretion disks, the inner structure down to just a few Schwarzschild radii could be probed by means of reverberation mapping. The standard model for the accretion disk around the SMBH in AGN postulates that the gas within the central few gravitational radii becomes extremely hot, optically thin and geometrically thick[12],[13]. The gravitational radius for a typical SMBH

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10 At z=1.6 (where 100 pc would subtend the smallest angular scale, namely 0.012”), a 16-m can still achieve the required resolution. An 8-m telescope, diffraction-limited at 0.3 μm (thus 0.01”) could observe targets up to z~1.6, but would lose them at higher redshifts since the Lyman-alpha emission would be redshifted to wavelengths longer than 0.3 μm, and the FWHM of the 8-m point spread function would increase to broader values.

with mass ~ $10^9$ $M_{SUN}$ is $r_g$ ~ $10^{15}$ cm; it is this central region that is therefore generally identified as being the source of the X-ray and line emission observed in AGN. This region is several orders of magnitude beyond the spatial resolution limit of any current telescope, but by means of reverberation mapping has been very successfully probed for a handful of objects in the local universe. An ATLAST instrumented with high-resolution (R ~ 30,000) spectrograph, a sensitivity at least ~100 times that of HST and high-contrast imaging in the UV/optical regime would provide a quantum leap in telescope capability that would enable this technique to be extended to the cosmological distances needed to truly probe the cosmic evolution of black holes. The consequence of the wealth of new observational details provided by ATLAST will provide the answers to the long-standing puzzles concerning the formation and co-evolution of galaxies and their central black holes.

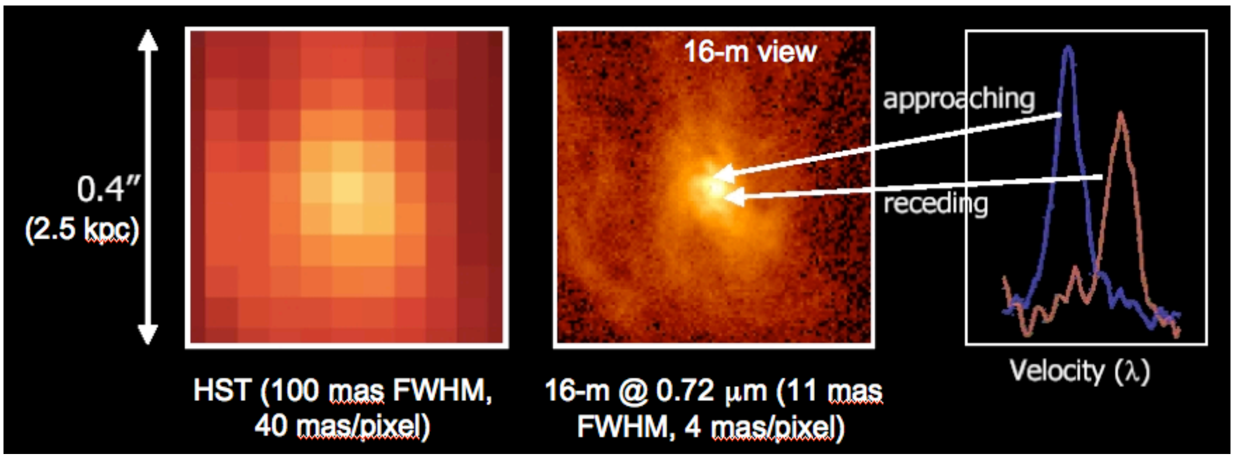


**Figure 4:** A nuclear disk of radius 190 parsecs (30 milli-arcseconds [mas]) observed in rest-frame Lyman alpha emission at high redshift, z = 5. **(Left)** Appearance of the disk as it would be seen with HST (2.4-m); **(Middle)** Appearance of the disk with a 16-m space telescope; **(Right)** spectra of gas approaching and receding in the central few hundred parsecs, enabling a direct measurement of the black hole mass at z~5 in this example.

### *2.4 The Growth of Structure: Direct Tests of the Gravitational Instability Paradigm*

Following the WMAP measures of the CMB, a number of ongoing or planned experiments (e.g., determining the equation of state of dark energy, direct measures of the cosmic expansion) are about to transform "cosmo-dynamics" – the kinematics of the cosmic expansion and its causes (primarily dark matter, dark energy) – into a high-precision, high-accuracy science. These experiments are about to provide the definitive tests of the hot big—bang cosmological paradigm. The same, unfortunately, cannot be said of the gravitational instability paradigm as the driving physical mechanism behind the formation of galaxies and larger structures. In large part, this is due to our current inability to make systematic, robust measures of the mass of cosmic structures and of the properties of their stellar populations (total mass, star formation rate, age, chemical content) across a significant fraction of the age of the universe. This problem is further compounded by the extreme difficulty to model, from first principles, star formation and its evolution in galaxies as a function of the structural properties of the underlying dark matter structures (mass, concentration, angular momentum, environment). The tremendous spectroscopic sensitivity of ATLAS combined with its very high angular resolution will revolutionize the field of galaxy formation, because it will finally enable direct measurements the key properties both the dark and visible components of structures and map their evolution in time with a similar degree of precision as cosmo-dynamics.

Legacy surveys with HST, Spitzer, Keck and the VLT have shown that the bulk of the stellar mass in galaxies and the Hubble types assembled at between $z$ ~ 3 and $z$ ~ 1, by which time the Hubble sequence was essentially in place (refs.) To understand galaxy formation, therefore, we must follow the growth of mass and stellar populations over this key cosmic period. The total (dynamical) masses of galaxies can be measured by means of gas kinematics from absorption spectroscopy of background galaxies, if sufficient spectroscopic sensitivity is available, essentially using galaxies in the same way as bright quasars have been used to study the intergalactic medium. For accurate kinematic information to be derived from the observations, 5 to 10 independent probes of the kinematics out to large radii, approximately 100--200 kpc, will need to be obtained for each targeted galaxy. This requires the capability to carry out low to medium resolution spectroscopy (R ~ 1000 – 3000) of sources as faint as 30$^{th}$ magnitude (in z-band). Down to this flux limit, the surface density of UV-bright galaxies (in the UV rest-frame) with redshift $2.5 < z < 5$ is ~500 per square arcminute (CHECK). This means that there are approximately 60 galaxies in the background of a galaxy at $z \sim 2$ within 100 kpc, or ~12 arcseconds, from its center. These galaxies provide as many lines of sight through the halo of the target galaxy from which it is possible to derive the radial velocity, effectively probing spatially-resolved kinematics of the gas around the $z \sim 2$ galaxy with a spatial resolution of roughly 25 kpc. Useful absorption features include the MgII absorption line at 0.28 μm, which in QSO Lyman-limit systems correlates well with neutral hydrogen (Steidel et al. 1992), or the CIV feature (0.145 – 0.155 μm). The dynamical mass as a function of radius from the center of the $z \sim 2$ galaxy is then derived from the individual measures.

The high sensitivity of ATLAS will also enable spectroscopy of sub-halo galaxies embedded in large halos, down to the same magnitude limits discussed above. This will allow a direct measurement of the dynamical mass of the large halos by determining the velocity dispersion of the sub-halo galaxies and, thus, allow the halo mass growth to be determined as a function of redshift. At the same time, high S/N continuum spectra covering the rest-frame UV to far-red optical (I-band for the nominal 3 μm max wavelength of ATLAS) combined with an analysis of the spectral line diagnostics will enable direct determination of the key parameters of the stellar populations such as mass (from continuum spectroscopy), obscuration (from the Balmer decrement), age (from SED) and chemical abundances (from a number of metallicity indexes). This will, in turn, allow the evolution of the mass-to-light ratio and spectral type to be measured as a function of redshift, effectively reconstructing the assembly of the Hubble sequence.

## 3. SCIENCE REQUIREMENTS

The above science drivers lead to a UV/optical space telescope with an aperture of at least 8 meters. Some of the more stringent drivers point to an aperture twice this size. Hence, our current NASA concept study focuses on two telescope architectures that straddle the range in viable technologies: an 8-meter monolithic aperture telescope and a 16-meter segmented-aperture telescope. Both concepts will strive to incorporate the following baseline requirements:

- Wavelength range: 0.11 – 2.5 μm (stretch objective: 0.11 – 3 μm)
- Angular Resolution: Diffraction limited at 0.5 μm
- Three-Mirror Anastigmatic optical design to enable minimum[11] field of view of 5 arcminutes. Possible modification to include pick-off at Cassegrain focus for narrow (~1 arcminute) FOV UV observations.
- Wavefront Control: sufficient to enable characterization of spectra from terrestrial mass (<10 $M_{\mathbf{EARTH}}$) exoplanets in conjunction with one or more internal and/or external starlight suppression systems.
- Field of Regard: the entire sky over the course of one year

[11] The full Nyquist-sampled fields of view, dictated from studies of stellar populations and galaxy clustering, are ~8 x 8 arcminutes for the 8-m and ~5 x 5 arcminutes for the 16-m.

- Halo orbit at Earth-Sun L2
- Minimum mission lifetime: 10 years

It is possible that some of these requirements are in conflict with existing technical capabilities (e.g., ultra-high contrast imaging vs. high UV sensitivity). As part of the current study we will explore what technologies or methods need continued development during the coming decade in order to enable a telescope to be constructed in the 2020 timeframe with the above capabilities for a viable cost.

## 4. ARES V ROLE IN ENABLING LARGE OPTICAL SPACE TELESCOPES

The Ares V Cargo launch vehicle vastly reduces the risk associated with launching and deploying ATLAST. Ares V enables a fully deployed 8-meter monolithic telescope or a folded, segmented telescope with an aperture up to 24 meters to be flown in a single launch. However, this will require an Ares V fairing that is ~90% taller (but as wide) as the present, nominal baseline design. Without Ares V, the alternatives entail combining multiple launches with on-orbit assembly or, for an 8-meter class telescope, the use of a non-circular primary mirror, which would reduce resolution and sensitivity. The Ares V also enables the use of high-TRL telescope components. For the monolithic 8-m design, the ~55 mT capacity to Earth-Sun L2 of the Ares V enables the use of stiffer (but massive) ground-based mirror technology. For the segmented primary design, the Ares V enables the use of the JWST (2 petal) chord fold deployment for apertures up to 16.8 meters. The use of a circular monolithic mirror that requires no deployment mechanisms has obvious advantages and minimizes risk. The use of JWST-based deployment design for the 16-m segmented primary will, by the year 2015, be a heritage TRL9 technology.

The phase A – D costs associated with either ATLAST point design will be in the multi-billion dollar range. However, we believe that by relying on Ares V to simplify the design and by maturing lightweight mirror technology, these costs can be kept comparable to those for JWST (~$4B in FY07 dollars). Indeed, the phase A – D cost for HST was ~20% higher than that for JWST and, yet, JWST's aperture is 2.7 times larger and its mass is 40% less. The standard telescope aperture vs. cost curve does not apply when there is a major shift in the underlying technology. JWST is the demonstration that advanced technology enables us to build much larger telescopes for costs associated with older and smaller observatories. A similar leap should be possible in the next 10 – 15 years if the right technology is developed. Hence, a major component of our strategic mission concept study will be to assess the technology development required to bring lightweight mirror fabrication and materials to TRL6.

The large capacity of the Ares V vehicle, however, has the potential to break traditional cost vs. mass relationships further by removing the usual limits on astronomy payload mass. A recent detailed design study of an 8-m monolithic ATLAST, conducted at Marshall Space Flight Center, has yielded a cost estimate (**excluding** science instruments and operations) in the range $1B to $1.5B but with a very high mass (~44,000 kg) due to the use of a conventional ground-based mirror blank (~20,000 kg). This effectively shifts a mission that would nominally be priced for "above average" difficulty to one whose cost is historically consistent with a mission of "very low" difficulty[X]. However, ground-based mirror blanks have their own maximum size limit of just over 8 meters and that limit is not likely to be increased due to a variety of very significant technical considerations. Hence for space-based scientific investigations that require collecting areas larger than ~50 $m^2$ it will indeed be necessary to use a lightweight segmented primary aperture.

## 5. THE TECHNOLOGY DEVELOPMENT ROADMAP FOR THE NEXT DECADE

Our present ATLAST study is devoted to identifying the technological tall poles associated with constructing, deploying, and maintaining on-orbit performance of a large optical system. This will include defining and estimating costs for the demonstrators that would be needed in the coming decade to validate the technologies at TRL6. Our team consists of investigators at 3 NASA centers (GSFC, MSFC, JSC), the Space Telescope Science Institute, the Jet Propulsion Laboratory, several major universities, and two industry partners – Northrop Grumman and Ball Aerospace. The highest priority trade studies and investigations, all driven by a central set of science requirements, include:

- Optimization of the optical designs for ATLAST to ensure required PSF over required field of view.
- Requirements and technology developments for the wavefront sensing and control systems, including strategies for the initial phasing and maintenance of the optical alignment and interface between the optical telescope assembly and one or more deformable mirrors (used to reduce residual wavefront errors to levels needed for high contrast imaging).
- Requirements for starlight suppression as demanded by the exoplanet characterization science objectives. We will explore the issues associated with both an internal coronagraph and external occulter, building upon extensive work already done.
- On vs. Off-axis trade study – this segment is tightly integrated with the starlight suppression requirements.
- Devise a technology development plan that, if funded, would bring lightweight mirrors (<12 kg/$m^2$) to TRL6.
- Devise a technology development plan that would allow the above mirrors to be fabricated in ~2.4-meter class segments and for a cost at or below $1M/ $m^2$.
- Establish packaging concepts for integration on the Ares V vehicle, including detailing potential modifications to current Ares V baseline designs that explicitly enable supporting an ATLAST payload (e.g., design booster to be compatible with taller fairing).
- Requirements on, and technology development needed for, the thermal and pointing control systems, including sunshade, solar torque mitigation, fast steering mirror, and fine guidance system.
- Requirements on design modularity needed to enable on-orbit servicing and to reduce ground-testing costs.

The results of this study will presented to NASA and the NRC Decadal Committee sometime in the first quarter of 2009. A compelling scientific case exists for a next generation large. ATLAST enables unique science and compliments the science that can be done with large ground-based observatories. Furthermore, the Ares V provides a path to deploy ATLAST in a single launch with direct insertion to an Earth-Sun L2 halo orbit. The core ATLAST technologies have potential applications beyond astrophysics and could be further propelled by the requirements for future remote sensing facilities for national defense and Earth sciences. Beginning the technology development program required to bring key technologies to TRL6 in the coming decade that will enable us to build and operate an affordable ATLAST starting in the 2020 – 2025 timeframe.

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